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MIDWEST STRUCTURAL SCIENCES CENTER 2009 ANNUAL REPORT

William A. Dick

University of Illinois

AUGUST 2010
Interim Report

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14. ABSTRACT
The Midwest Structural Sciences Center is a collaboration between the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/RBSM SSC), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI), Wright State University, University of Cincinnati, and the University of Texas at San Antonio. The team works closely to simulate, model and test structures and materials for use in future air-and space-vehicles in a risk quantified design process.

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The Midwest Structural Sciences Center is a collaborative effort between the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/RBSM), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI), Wright State University (WSU), and the University of Texas at San Antonio (UTSA). The team works closely to simulate, model, test, and assess structures and materials for use in future air- and space-frames in a risk-quantified design process.

The University of Illinois Midwest Structural Sciences Center (MSSC) was established in February 2006 to expand rapidly the technical manpower available to the Structural Sciences Center at AFRL. The MSSC has the long-term objective of developing the knowledge base required for validated, risk-based tools for the design and simulation of spatially-tailored aero-thermo structures (STATS). In close collaboration with the scientific and engineering staff of AFRL/RBSM, faculty, staff and students from the universities will complete medium-term research projects (five- to ten-year horizons) in four key areas:

- Coupled thermo-mechanical-acoustic analysis and simulation of spatially-tailored aero-thermo structures
- Identification and definition of structural limit states for spatially-tailored aero-thermo structures
- Computational frameworks and methodologies for risk-quantified structural assessment of spatially-tailored aero-thermo structures
- Experimentation, verification, and validation

The team employs analytical, computational, experimental, personnel and financial resources from several university departments and AFRL organizations, and seeks additional resources as needed from other federal and non-federal sources. Outstanding facilities are available at all sites and are being applied to MSSC projects and programs. Graduate research assistants work with faculty at the universities and their AFRL/RBSM colleagues to evaluate and extend the understanding of materials and structures in aerospace structural components that experience extreme combined environments.

MSSC Technical Program Features

Risk analysis and quantification
Multiscale materials modeling
Generalized FEM for acoustic modeling
Sensitivity analysis
Experimental validation

MSSC Research Program Partners

Air Force Research Laboratory Air Vehicles Directorate, Structural Sciences Center
University of Illinois at Urbana-Champaign
Aerospace Engineering
Civil and Environmental Engineering
Computational Science and Engineering
Mechanical Science and Engineering
Wright State University
University of Texas at San Antonio

1 Introduction

1.1 Air Force Structural Sciences Mission

Future missions of the Air Force, such as prompt global strike and operationally responsive space access, will be performed with air/space vehicles now in conceptual design. However it is clear that the structural concepts needed to make such next-generation vehicles sufficiently durable and lightweight will involve novel structural arrangements and material systems. During typical operating conditions, aircraft are subjected to random loads due to engine noise and other acoustic vibrations. The random acoustic pressure load, combined with other extreme conditions like elevated temperatures, turbulence, etc., may lead to the failure of the aircraft structure.

The potential for reducing weight from using integrated functional structures is great, though designs that enhance damage tolerance are key to their success. Because of the intensity and complexity of combined loads on future vehicles, unprecedented integration of structural configuration and overall material behavior — at the design stage — is required to meet damage tolerance demands. Cost and flight environment requirements preclude the traditional design-build-test-redesign approach; hence this integration must be done largely through simulation and digital prototyping. The focus of our research program is precisely this integration by provision of next-generation, validated, computational simulation capabilities for damage evolution and mitigation in structures composed of novel materials under combined loading, especially thermal-mechanical-acoustical (TMA) loads.

The Air Force capabilities desired in the future require the structural integrity of aircraft during their high-performance operations in extreme environments. This unprecedented goal demands new techniques of analysis, design and manufacture, and specially-engineered materials/structures including functionally graded materials (FGM). The intrinsic and epistemic uncertainties in such extreme loads and the structural behaviors of new materials are significant and propagated into the performance of the air vehicle systems. This causes unquantified risks of structural failures during the operations. We are developing a probabilistic framework to identify/synthesize the uncertainties in the components so that risk-quantified designs of aircraft systems can be achieved. It will also enable design modifications and improvements that minimize the risks within the available budget and constraints.

Modeling/simulation — Used in reliability analysis, design, and for designing effective experiments

Experiments — Data used for parameter identification studies to improve modeling effort and validation of simulations

Risk/reliability — Algorithms used for reliability analysis, parameter identification and design

1.2 Midwest Structural Sciences Center

The Midwest Structural Sciences Center is a collaborative effort among the Structural Sciences Center, Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/RBSM), and a team of faculty, graduate students, and professional staff researchers of the University of Illinois at Urbana-Champaign (UI), Wright State University (WSU), and the University of Texas at San Antonio (UTSA). The team works closely to simulate, model, test, and assess structures and materials for use in future air- and space-frames. The MSSC team is viewed as a "living organization" whose members may change over time to meet the needs of the collaborative partnership.

The team employs analytical, computational, experimental, personnel and financial resources from all four organizations, and will seek additional resources as needed from other federal and non-federal sources. Outstanding facilities are available at all sites and will be applied to MSSC projects and programs. Graduate research assistants work with faculty at the universities and their colleagues at

AFRL/RBSM to evaluate and extend our understanding of materials and structures in aerospace structural components that experience extreme combined environments.

Collaboration among the partners is frequent (near-daily) and intense (co-advised research projects and graduate theses, teamed simulation and experiments, co-authored journal articles and project proposal submissions, etc.). Computational resources, graduate assistantships, experimental facilities and AFRL/RB visitor office spaces have been earmarked to directly support the MSSC, as have graduate student tuition waivers.

High-performance hypersonic aircraft are expected to have stringent structural requirements, especially in regard to STATS components. Many of these structural components may include specialty high-performance metal alloys or functionally-graded materials (FGM), each specifically designed and manufactured to address the combined thermo-mechanical-acoustic loadings unique to hypersonic applications. MSSC research is developing models that account for the damage progression in both the ductile and brittle phases of FGMs. Especially important is the development of efficient methods for quantifying the uncertain responses and the risks of STATS. Among other techniques, methods to identify important input uncertainties through sensitivity analyses that allow us to focus on the dominant uncertainties that threaten successful risk-quantified structural design (RQSD) are envisioned. Our work focuses on carefully selected, small-scale aircraft substructures that can be fully characterized experimentally. These structures are employed in assessing new methodologies for predictive science tying together RQSD, high-fidelity simulations, and novel experimental techniques.

MSSC Team Members

University of Illinois

Bodony — Acoustic response prediction
Brandyberry — Uncertainty quantification and risk analysis
Duarte — GFEA, structural analysis, multiscale analysis
Geubelle — Multiscale analysis, FEA
Lambros — Experiments, high strain rates, FGM
Paulino — FGM, Multiscale analysis, structural analysis
Sehitoglu — Thermomechanical response, experiments
Song — Risk, reliability, stochastic events, FEA
Tortorelli — Sensitivity, optimization

Wright State University

Penmetsa — Risk, failure probability assessment

University of Texas at San Antonio

Millwater — System reliability

AFRL/RBSM

Acoustic experiments, aeroframe design, operating environments, large-scale structural testing

Existing constitutive materials models are generally phenomenological, i.e., they are based on some empirical formulae (e.g., power law) to be fitted to laboratory tests. The phenomenological models rarely work well for advanced materials subjected to extreme conditions since they rarely account for the significant microstructure changes under the extreme environment. Thus novel, physically based constitutive models are being developed under the MSSC umbrella.

Successfully modeling fatigue in aerospace structures requires detailed knowledge of the various structural and material failure modes across the wide variety of fatigue loadings possible. In parallel to our simulation and RQSD tasks, Center researchers conduct series of experiments to determine the relative importance of low cycle, high cycle, and fatigue crack growth in materials subjected to thermomechanical and acoustic fatigue. Experiments are being performed to understand the interaction between the high stresses associated with thermal loading, superimposed with ultrahigh frequency-induced stresses from an acoustic-type loading. In each project, university investigators from UI, WSU, or UTSA are teamed with RBSM personnel to encourage tight relationships between university and government researchers.

2 Technical Project Progress

A — Coupled Thermo-Mechanical-Acoustic Analysis and Simulation of STATS

A1 *Design of STATS using Topology Optimization (Glaucio Paulino, Fernando Stump, Larry Byrd) — Completed*

A2 Generalized FEM Analysis for Transient Simulations (C. Armando Duarte, Patrick O'Hara, Thomas Eason)

A3 Integrated Fluid/Structure Interaction Simulation (Daniel Bodony, Philippe Geubelle, Mahesh Sucheendran, Adam Kuester, Halvorson, Joseph Hollkamp, Robert Gordon)

A4 *Analytical Prediction of Dynamic Response of FGM (Anthony Palazotto, Reid Larson) — Completed*

A5 Multiphysics, Coupled Analysis of Extreme-Environment Structures (Daniel Bodony, Philippe Geubelle, Christopher Ostoich, S. Michael Spottswood)

A6 Non-Intrusive Implementation of Multiscale Capabilities in a General Purpose FEA Platform (Thomas Eason, C. Armando Duarte, Jeronymo Pereira)

B — Identification and Definition of Structural Limit States for STATS

B1(x) *Failure Analysis of FG Aircraft Components in Combined Environments (Yonggang Huang, Jianliang Xiao, Eric Tuegel) — Redefined in 2007*

B2(x) *Imperfections and Defect Tolerance of Aircraft Shells and Structures (Daniel Tortorelli, Martin Ostoja-Starzewski, Ravi Bellur-Ramiswamy, Thomas Eason) — Redefined in 2007*

B1 Mechanism-Based Cohesive Failure Model for Functionally Graded Aircraft Components and Structures (Eric Tuegel, Glaucio Paulino, Arun Gain)

B2 Imperfections and Defect Tolerance of Aircraft Shells and Structures (Daniel Tortorelli, Seth Watts, Thomas Eason)

C — Framework and Methodologies for Risk-quantified Structural Assessment of STATS

C1 Uncertainty/Risk Quantification Methods for STATS (Junho Song, Young Joo Lee, Eric Tuegel)

C2 Validation of Simulations Having Uncertainties in Both Simulation and Experiments (Mark Brandyberry, Jason Gruenwald, Mark Haney)

C3 *Risk-Based Design Plots for Aircraft Damage Tolerant Design (Ravi Penmetsa) — Completed*

C4 System Reliability with Correlated Failure Modes (Harry Millwater, Luciano Smith, Daniel Sparkman, David Wieland, Eric Tuegel)

C5 Identifying Structurally Significant Items using Matrix Reanalysis Techniques (Ravi Penmetsa, Bhushan Kable, Vankat Shanmugam, Eric Tuegel)

D — Experimentation, Verification, and Validation

D1 Experimental Investigation of Thermomechanical Fatigue Failure Modes (Huseyin Sehitoglu, Chrisos Efstathiou, S. Michael Spottswood)

D2 Development of Experimental Techniques for Validating a Coupled Thermomechanical Fatigue Simulation Framework (Jay Carroll, John Lambros, S. Michael Spottswood)

D3 Thermomechanical Fatigue of Hastelloy X: Role of Combined Loading on Material Response (Wael Abuzaid, Huseyin Sehitoglu, S. Michael Spottswood)

Italic — Concluded projects

A — Coupled Thermo-Mechanical-Acoustic Analysis and Simulation of STATS

Four projects are being pursued to address the coupled thermomechanical-acoustic analysis and simulation of STATS. The first project in this thematic area is “Generalized FEM Analysis for Transient Simulations” (A2), led by Armando Duarte (UI) and Thomas Eason (AFRL/RBSM). A computational framework to simulate the behavior of heterogeneous shell structures operating under a broad range of service conditions is being developed. The intent of the project is to reduce the overall computational time requirements, while simultaneously increasing the local solution resolution.

Philippe Geubelle and Daniel Bodony (UI) and Mike Spottswood and Joe Hollkamp (AFRL/RBSM) have teamed with others in two closely related projects. The first project (A3), “Integrated Structural/Acoustic Interaction Simulation of STATS,” is based on work done in the complementary UI/DOE Center for Simulation of Advanced Rockets (CSAR). The team is developing 2-D and 3-D coupled structural-acoustic codes aimed at capturing the complex interaction of acoustic waves impinging STATS and those associated with the dynamic response of the structure. The project is two-pronged: development of a parallel, coupled structural acoustic solver, and characterizing the thermo-acoustic test environment in the AFRL Sub-Element Facility (SEF). The second project (A5), “Multiphysics, Coupled Analysis of Extreme-Environment Structures,” focuses on using the new code suite to assess the loads on a hypersonic vehicle panel.

Two projects have been completed in the A Group. The first (A1), entitled “Design of STATS using Topology Optimization,” was led by Glaucio Paulino (UI) and Larry Byrd (AFRL/RBSM). The next generation of high-performance hypersonic aircraft in the Air Force is expected to demand stringent structural requirements, especially in regard to STATS components. Continuum (as opposed to traditional) topology optimization was used as a rational means to obtain innovative structural designs, which will improve performance and lower costs. This project sought to develop a multiscale, 2- and 3-D continuum topology optimization that accounts for material gradient effects. By multiscale we mean that the framework optimizes both the material and component scales. AFIT Professor Anthony Palazotto completed Project A4, “Analytical Prediction of Dynamic Response of FGM.” Thermal deformation of cylindrical composite shells was investigated in A4, in which a thermal distribution represents a varying heat environment over an aircraft surface. This project compared FGM to conventional metals for aircraft applications.

A2 Generalized FEM Analysis for Transient Simulations (Duarte, O’Hara, Eason)

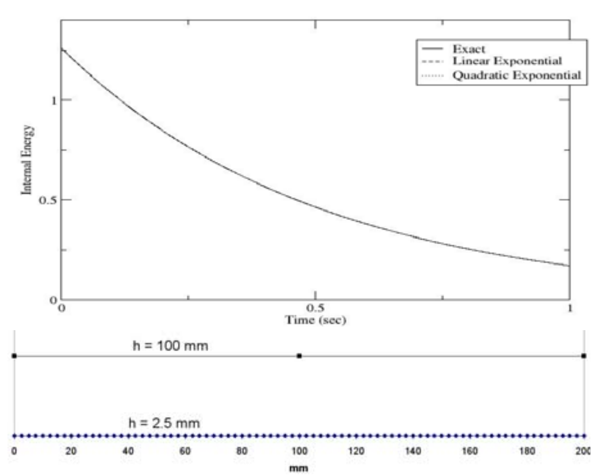

Figure Dua-1. Shows internal energy versus time curves for simulations using special enrichments, as well as for exact curve. Also shows mesh density used for special elements (top) compared to that used with polynomial elements (bottom).

The ability to resolve transient, localized behavior on a fixed, coarse mesh is of great interest for the analysis of hypersonic flight vehicles. The generalized finite element method (GFEM) is a good candidate methodology in that it has the ability to insert local information into the coarse mesh via the specially-tailored GFEM shape functions. A 1-D example in which a sharp front moves across a domain is illustrated, along with the accompanying meshes used for the analysis. In this instance, an analytical enrichment known to represent the solution is used merely for proof-of-concept. As can be seen, great accuracy can be obtained on a very coarse mesh. In this case, another concern of transient analysis is addressed, in the form of prohibitively small time-steps required for both spatial accuracy, and temporal stability when explicit time integration is used. With the coarse mesh, larger time-steps are permitted, without the loss of accuracy that would occur with standard FEA.

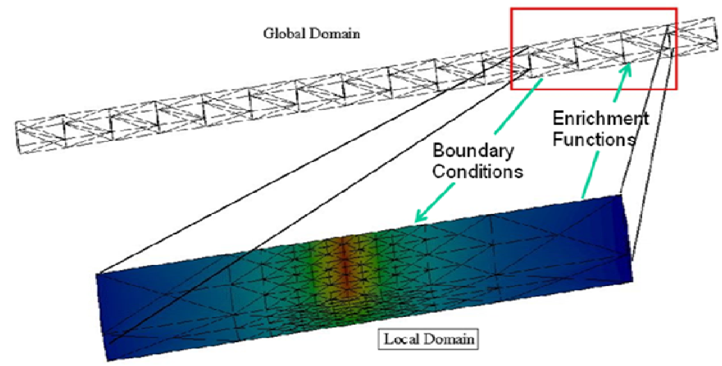

Figure Dua-2. Beam subjected to laser heating. Illustrates two-way information transfer of proposed methodology.

In 2009 we have moved well beyond the 1-D proof-of-concept in the 1-D case. The main focus of the research effort is on 3-D analyses. The use of analytical enrichments is overly specific, so we propose to build enrichment functions on the fly, through the solution of BVPs. With this—the GFEM with global-local enrichments (GFEM^{gl})—in a very general manner we can build specially-tailored enrichment functions for problems that we have no prior knowledge of the solution. In our methodology, we rely on a fixed, coarse mesh at the scale for which we would like to analyze the behavior. From this coarse mesh we select the regions of localized interest, and extract them from the global mesh. On these local domains, we perform our hp-adaptivity, and using boundary conditions from the global domain we solve the resulting BVP. The solution is inserted into the global mesh via the partition-of-unity. We have then constructed shape functions that are specially constructed with the local behavior in mind. As a result, we can move these enrichments around where they are needed, and we have no need to alter the global mesh throughout the entire transient simulation, At the same time we provide shape functions capable of capturing the local behavior on the structural scale.

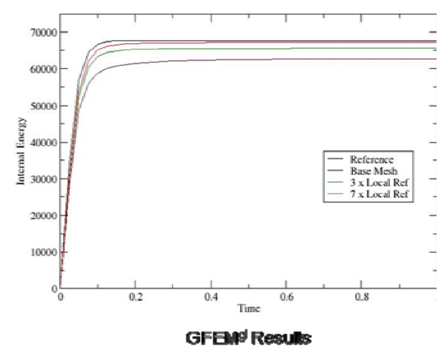

Figure Dua-3. Internal energy versus time curves for GFEM^{gl} as well as a reference curve generated with hp-GFEM.

Our proposed methodology has been applied to a beam subjected to laser heating, as shown in Figure Dua-2. The global elements shown are each one inch in width, and the radius of the laser is 0.01 inches. Results generated using the proposed methodology are shown in Figure Dua-3, as well as a reference curve generated using hp-GFEM. From the plots it can be seen that the GFEM^{gl} produces results on a coarse mesh that are similar to those generated using a highly graded mesh, with a significantly smaller element size.

A3 Integrated Fluid/Structure Interaction Simulation (Bodony, Geubelle, Sucheendran, Kuester, Halvorson, Hollkamp, Gordon)

During the past year the focus was on two activities: (i) development of a parallel, coupled structural-acoustic solver; and (ii) acoustic characterization of AFRL Sub-Element Facility (SEF) using a quasi-one-dimensional approach.

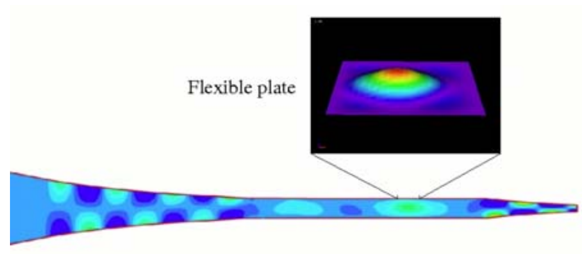

Figure Bod-1. Fully-coupled simulation of the SEF for a single frequency planar acoustic wave input.

In order to develop a coupled acoustic-structural solver, the compressible, non-linear fluid solver, *RocfloCM*, was integrated into the *Rocstar* suite of numerical codes. The structural solver, *Rocfrac*, which was already integrated into *Rocstar*, has been optimized over the past year and has been verified using a 3-D dynamical cantilever problem. During this period mass-proportional damping was implemented in *Rocfrac* to simulate problems with structural damping. Communication between *RocfloCM* and *Rocfrac* is facilitated by the tools in *Rocstar*.

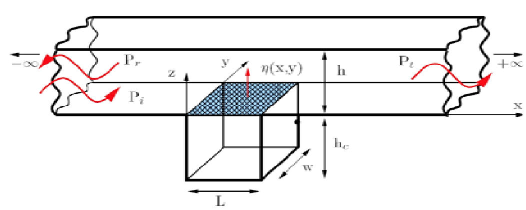

Figure Bod-2. Analytical verification problem schematic.

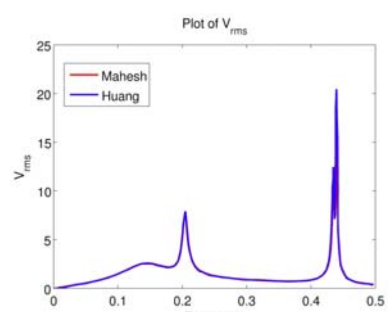

Figure Bod-3. Comparison of present results with those of Huang (2006).

Using *RocfloCM* for solving the governing equations in the acoustic domain and using *Rocfrac* for the solution in the structural domain, a coupled structural-acoustic interaction simulation of the SEF was carried out. Figure Bod-1 shows the contour plot of the normal component of momentum in the fluid domain

and vertical displacement of an aluminum plate. Due to the disparate computational requirements in the fluid and solid domain, the capability of having separate processors for the fluid and solid domain was introduced. Since the computational requirements for solution in the fluid domain was much larger compared to the solid domain, the simulation used 64 processors in the fluid domain and 2 processors in the structural domain.

To verify the code, an analytical solution for a closely-related structural-acoustic interaction in an infinite uniform duct with a cavity-backed flexible rectangular plate was developed. Figure Bod-2 shows the geometry and other details of the problem. Figure Bod-3 shows the comparison of the plate velocity root-mean-square, V_{rms}, computed from the analytical solution and compared with existing results. A numerical prediction of the same problem using the coupled fluid/structure solver is currently underway.

The acoustic characteristics of the facility were investigated to provide boundary condition information of the numerical predictions of the SEF. By approximating the facility as a quasi-one-dimensional duct, a Matlab code was written that solves the 1-D linearized Euler equations in the fluid domain inside the SEF with the area variation of the duct taken into account. Impedance boundary conditions and modeling the losses in the facility were implemented to replicate the experimental results. Figure Bod-4 shows the comparison of experimental data from the SEF with the Matlab code. Another quasi-one dimensional code was written to estimate the transfer function of the SEF in the spectral domain. The code takes into account the area-variation of SEF in discrete steps.

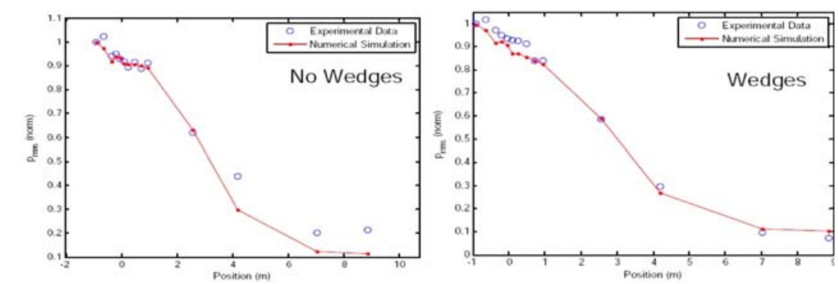

Figure Bod-4. Estimation of the acoustic properties of the SEF for (left) hard-walled termination and (right) acoustic wedge termination.

Future directions include verifying the coupled solver by comparing the numerical and analytical solutions of the aforementioned duct/cavity problem. The verified code will then be used to estimate the acoustic-structure coupling coefficients used in the reduced-order models developed by Hollkamp and Gordon and to investigate the effect of the flow velocity on the structural/acoustic damping response.

A5 Multiphysics, Coupled Analysis of Extreme-Environment Structures (Bodony, Geubelle, Ostoich, Spottswood)

The first year of project A5 was dedicated to (i) identifying the environmental loads on a mid fuselage panel of a hypersonic vehicle; (ii) modifying an existing finite element (FE) structural dynamics solver to solve linear, transient thermal problems in a structure; and (iii) coupling the thermal FE solver to the high fidelity, nonlinear, finite difference Navier-Stokes solver, *RocfloCM*, used in project A3. The tools developed will be necessary to accurately model the thermal loads experienced in the hypersonic environment. Currently, the tools are being validated against data from an experimental aerothermal examination of hypersonic flow over bowed thermal protection panels.

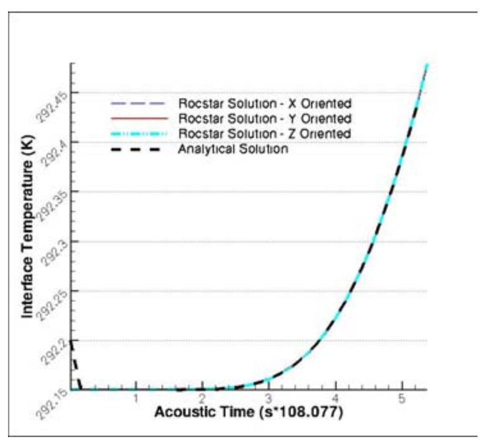

Figure Ost-1: Verification of fluid-structural-thermal coupling.

Characteristic of the hypersonic environment are the high temperatures that exist in the flow field, which negate physical assumptions about the behavior of the gas that are

valid in lower Mach number regimes. In order to capture the fluid properties at these temperatures, a thermally perfect gas model (specific heats are functions of temperature) was implemented in *RocfloCM* to replace the previously implemented calorically perfect gas assumption. In addition, a preexisting, transient FE structural dynamics solver was modified to create a transient FE thermal structure solver, *Roctherm*. *Roctherm* was written to lend itself to further modification to a non-linear solver should it be necessary in the future. *Roctherm's* accuracy was verified by comparison with an analytical solution of heat conduction in a 1-D steel bar.

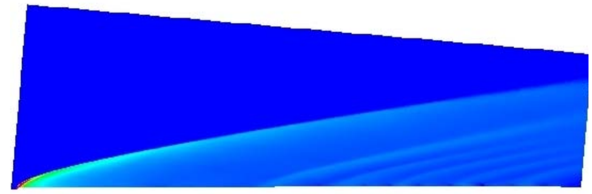

Figure Ost-3: 2-D simulation of hypersonic flow over bowed TPS panels.

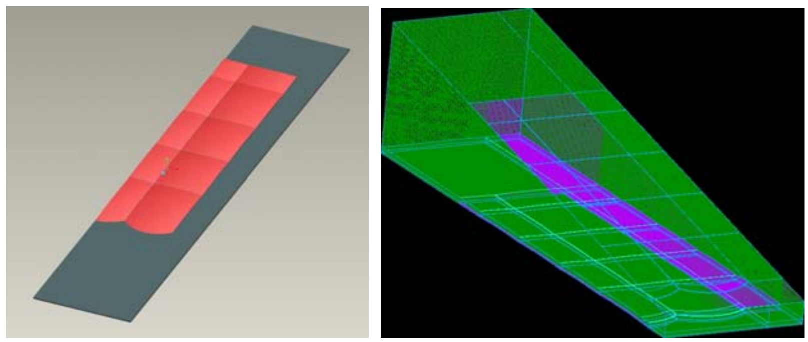

Figure Ost-2: (left) Solid model of quilted TPS domes for use in coupled fluid-thermal structure simulation. Geometry is cut in half to exploit symmetry of the situation; (right) 4,790,760 grid-point mesh of fluid domain in coupled fluid-thermal structure simulation.

Roctherm was coupled to *RocfloCM* by utilizing preexisting software developed at the University of Illinois at for the purpose of facilitating communication between several solvers to allow for multi-physics simulations. The coupling was accomplished by passing interface heat flux information from the fluid domain to the structural thermal domain, while passing interface temperature information from the thermal structure domain to the fluid domain. This configuration has been shown to encourage numerical stability at the fluid-solid interface [Giles M. B., 1997. Stability analysis of numerical interface conditions in fluid-structure thermal analysis. International Journal for Numerical Methods in Fluids, 25:431–436]. The coupling of the two codes was verified in Figure Ost-1 by comparison with the analytical solution of conduction through a two-layer laminate.

The current fluid-thermal structure coupled simulation is aimed at reproducing results of a wind tunnel experiment of hypersonic flow over bowed TPS panels [Hunt L. R. and Glass, C. E., 1988. Aerothermal tests of quilted dome models on a flat plate at a mach number of 6.5. NASA technical paper 2804, NASA]. These panels were tested in the late 1980s as a candidate for an exo-atmospheric vehicle. A solid model of the quilted TPS panels was created to reproduce the experimental setup as was described the report (Figure Ost-2, left). This solid model served as both a surface over which to generate the mesh in the fluid domain (Figure Ost-2, right), and a volume in which a solid, FE mesh will be created. Due to the high computational cost of running the high-fidelity *RocfloCM* solver, the initial and boundary conditions of the simulation were estimated by running a numerical simulation over a similar 2-D geometry using a low order commercial code (Figure Ost-3). The coupled simulation will produce surface temperature and wall heat flux data to be compared to the experimental results of Hunt & Glass.

B — Identification and Definition of Structural Limit States for STATS

Professor Glaucio Paulino (UI) and Eric Tuegel (AFRL/RBSM) have joined to develop a scalable cohesive failure model for functionally graded materials and structures based on the experimentally identified mechanisms (B1). “Mechanism-based Cohesive Failure Model for Functionally Graded Aircraft Components and Structures” is developing a model that can be used to predict the crack nucleation, initiation and progressive growth in various material systems. These investigators will collaborate directly with

experimentalists to link the microstructures to the macroscopic failure mechanisms, and determine the actual cohesive failure model parameters.

The second project in this theme area (B2), "Imperfections and Defect Tolerance of Aircraft Shells and Structures," will establish a methodology that identifies the optimum spatial constituent distribution to achieve the desired performance for STATS. Daniel Tortorelli (UI), Thomas Eason (AFRL/RBSM) and their colleagues will develop a methodology to optimize functionally graded materials with applications in STATS. The approach is to quantitatively characterize the microstructure of FGMs, with the goal of developing a statistical mapping of the microstructure's phase morphology to the composite material's thermomechanical properties and damage resistance. In conjunction with other ongoing projects, this will enable the ability to optimize FGMs relative to certain parameters (e.g. weight) while maintaining acceptable levels on the structural response (e.g. stiffness).

B1 Mechanism-Based Cohesive Failure Model for Functionally Graded Aircraft Components and Structures (Tuegel, Paulino, Gain)

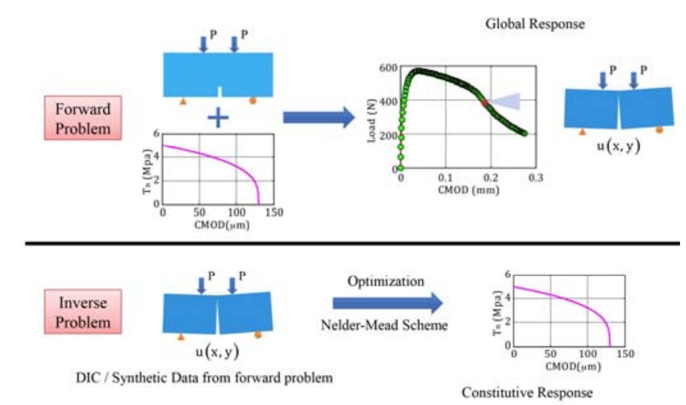

Figure Pau-1: Forward and inverse problem.

Damage and failure of spatially tailored aero-thermal structures under extreme loading conditions is a challenging problem of national interest and technological relevance. Such structures can be properly assessed with a nonlinear model of cohesive fracture, which is able to predict crack nucleation and failure sites.

Both direct and inverse fracture problems are investigated in this work as illustrated by Figure Pau-1. In the direct problem, the input fracture properties are known, and the output is displacements. In the inverse problem, a hybrid technique blending computations and experiments is used to extract the cohesive properties. For instance, by means of the experimental displacement field (input) obtained from digital image correlation (DIC), an optimization algorithm is used to compute the cohesive constitutive parameters (output).

With respect to the direct problem, we have conducted a detailed investigation of the shape of the CZMs on fracture simulations. The shape of CZM along with fracture energy and cohesive strength plays a critical role in the simulations. Numerical simulations were carried with a single edge notch beam using an ABAQUS user-element subroutine in conjunction with bilinear and trapezoidal CZMs. Investigation of the influence of fracture energy and cohesive strength was also conducted.

With respect to inverse problems, the hybrid technique is employed. A finite element code was developed to solve the forward problem. The elasto-plastic nature of the bulk elements is considered by means of J2 plasticity, though other models can be considered. Results in the form of global response of the system were verified using ABAQUS. The inverse analysis framework is developed to extract the underlying CZM constitutive parameters. The Nelder-Mead optimization is employed in which the location of a number of points (control points) is optimized, and later the CZM is obtained by interpolation of these control points. Inverse analysis requires the displacement fields of the specimen, which are obtained either from the forward problem (synthetic data) or from DIC. Presently, the code has been verified only for synthetic data obtained from various loading points in the forward problem. Typically, an inverse analysis code requires an initial guess from the user. Various initial guesses were used to test the code, as illustrated in Figures Pau-2 and Pau-3. In order to resemble actual experiments, the computer code was tested with synthetic data added with noise. The code has been successful in all the tests so far.

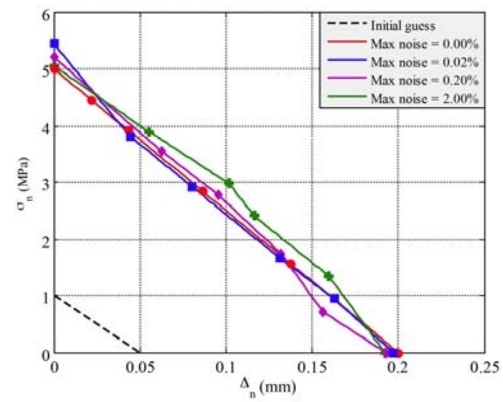

Figure Pau-2: Extracted cohesive zone model from inverse analysis (shape regularization technique) using synthetic data with different levels of noise.

An alternate computational technique to model forward and inverse problem was developed using the Park-Paulino-Roesler (PPR) potential for the cohesive model. In this technique, rather than optimizing the location of control points, three parameters (fracture energy, cohesive strength and shape parameter) are optimized. With these three parameters, the CZM can be readily obtained in closed form. The inverse code using PPR was successfully tested for all the cases in which the first scheme was tested for.

In an effort to integrate experiments and computations through the hybrid technique, work is being performed to extract cohesive fracture properties of PMMA using experimental displacement fields from DIC images. This work is being done in collaboration with project D2 (Spottswood, Lambros, Carroll). Another recent collaborative work involves the development of a probabilistic cohesive zone model. This ongoing work is being done in collaboration with Prof. Ravi Penmetsa and his research group at Wright State University (C5).

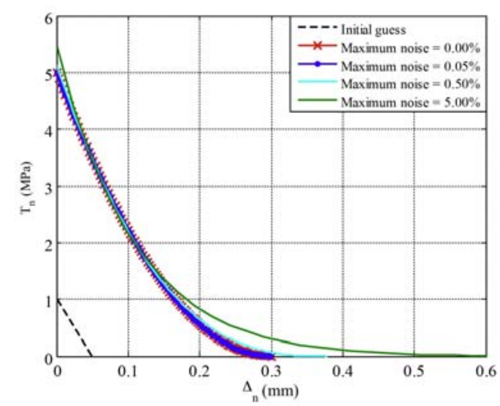

Figure Pau-3: Cohesive zone model from inverse analysis (PPR model technique) using synthetic data with different levels of noise.

B2 Imperfections and Defect Tolerance of Aircraft Shells and Structures (Tortorelli, Watts, Eason)

This project will develop a methodology to optimize functionally graded materials (FGMs) with applications in Spatially Tailored Aero-thermal Structures (STATs). The approach is to quantitatively characterize the microstructure of FGMs, with the goal of developing a statistical mapping of the microstructure's phase morphology to the composite material's thermomechanical properties and damage resistance. In conjunction with other ongoing projects, this will enable the ability to optimize FGMs relative to certain parameters (e.g. weight) while maintaining acceptable levels on the structural response (e.g. stiffness).

The development work for this project has been divided into several necessary tasks. The first is to generate a library of images of FGM candidate materials. As reported in the 2007-08 MSSC Annual Report, a methodology has been developed for obtaining micrographs of the $Ti\text{-}ZnO_2$ material system, and a

collection of images has been created. Future work will include translating these methods to the imaging of Ti-TiB material systems, and developing the ability to generate accurate 3-D images of a microstructure through serial sectioning or microtomography.

The second task is to develop numerical descriptions of the morphology of spatial patterns (e.g. the material microstructure). Applying such descriptors to the micrographs generated as discussed above allows us to quantitatively describe the microstructure. Such descriptions will subsequently be used to instantiate numerical microstructure models with morphological characteristics similar to those of the candidate FGM material. This task necessitates several subordinate tasks, and we have devoted much of our efforts over the past year to this topic. We have adapted methods from the literature to robustly segment images into disjoint sets — every point is unambiguously assigned to either the inclusion or the matrix phases — with well-defined boundaries. We have extended a family of recently introduced morphological descriptors, the Minkowski valuations, which describe the complexity of microstructural patterns as a family of arbitrarily high-ordered tensors.

We have written several computer programs to implement various aspects of the developments mentioned above. Some early pixel-based computer programs were abandoned when we showed they were not accurate for smooth microstructural features. Subsequent programs implement segmentation algorithms, shown schematically in Figure Tor-1, which accurately model smooth boundaries with sub-pixel resolution. Future work in this area involves adjusting certain control parameters in the segmentation algorithm to best suit the FGM candidate materials, and further optimizing the computer codes.

We have begun making inroads into the third task, the correlation of phase morphology to properties of the composite material. By meshing the segmented microstructural images (Figure Tor-2) and perform-

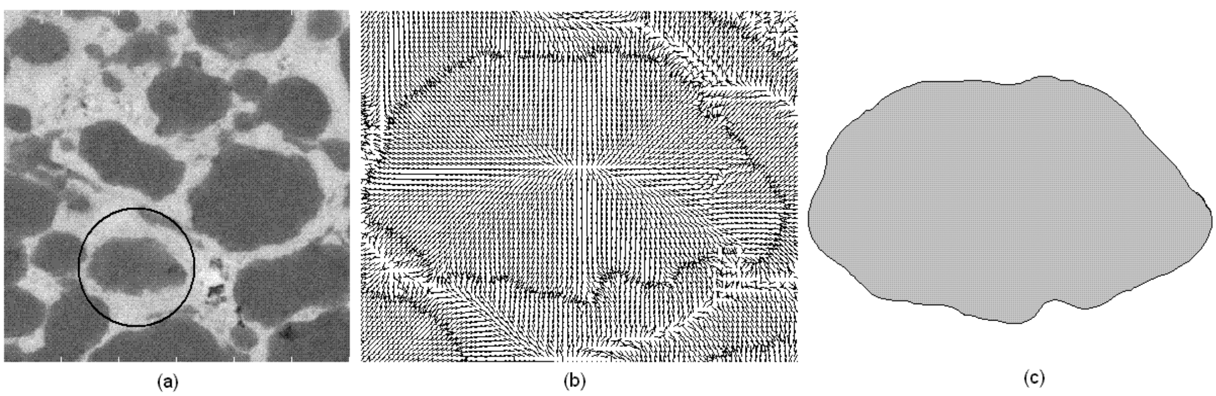

Figure Tor-1: Schematic of image segmentation. (a) circled inclusion in SEM micrograph; (b) non-uniform, anisotropic smoothing operator is applied to the image grayscale gradient, yielding a smoothed gradient vector field; (c) closed membranes are initialized in field and deformed to minimize energy functional that causes them to fit inclusion shape.

ing finite element analyses, we can place bounds on the homogenized properties of the composite. So far we have considered the homogenized elasticity tensor, modeling each phase with isotropic, elastic material properties. Our analysis shows that the Minkowski valuations are superior descriptors relative to the more common two-point correlation functions.

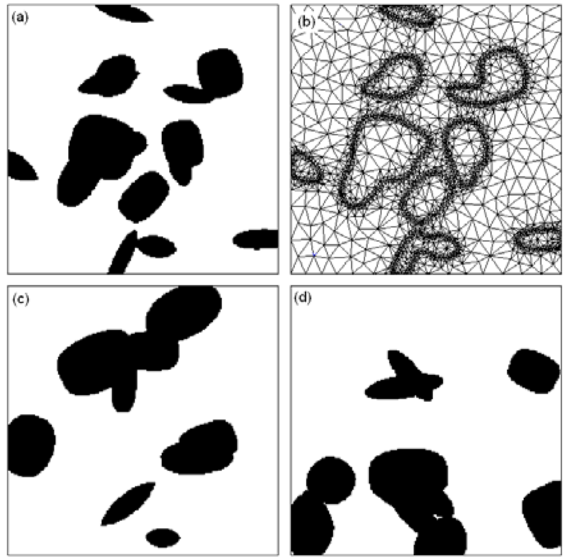

Figure Tor-2: Meshing microstructures and homogenized properties. Microstructure (a) is meshed (b) by locating nodes along boundary identified using process of Figure Tor-1. FEM simulation of (c) and (d) shows them to have differing maximum stiffness, yet essentially identical two-point correlation functions. Minkowski valuations easily discern differences that lead to different properties.

In the fourth task, we will combine the developments made previously, and use techniques from topology optimization to create numerical microstructures with morphological characteristics sampled from statistics generated by analysis of the SEM micrographs of candidate FGM materials. The FEM-based homogenization techniques will then be used to bound composite properties of interest, and we will seek correlations between the morphology and composite properties.

C — Framework and Methodologies for Risk-quantified Structural Assessment of STATS

There are four projects underway in the broad area of risk-quantified structural assessment. The application of STATS in next generation airframes will largely depend upon confidence enabled through risk-quantified structural assessment.

In the first (C1), Junho Song (UI) and Eric Tuegel (AFRL/RBSM) lead a project to develop novel "Uncertainty/Risk Quantification Methods for STATS." This project develops efficient methods for quantifying the uncertain responses and the risks through computational simulations. Also developed are the methods to identify important input uncertainties through sensitivity analyses, which will allow a focus on the dominant uncertainties during the risk-quantified structural design (RQSD). AFRL/RBSM will provide a small-scale example of aircraft substructure, such as a wing torque box, to use as an example throughout the development of uncertainty/risk quantification methods.

The second project in this theme (C2) focuses on "Validation with Uncertainties in Both Simulation and Experimental Results." Led by Mark Brandyberry (UI) and Eric Tuegel (AFRL/RBSM), this research team will provide accurate simulation tools with which to make predictive calculations of physical processes of interest. Simulations are, by their nature, approximations to reality, and as such have various

uncertainties associated with their results. Often it is difficult to adequately assess these uncertainties due to the computational time required to make the runs, and thus it is desired to minimize the number of simulations required. This effort seeks to understand the relationship between input uncertainties and simulation confidence when constrained by a limited number of computational runs.

"System Reliability with Correlated Failure Modes" (C4) is led by Harry Millwater (UTSA) and Eric Tuegel (AFRL/RBSM). In it a system reliability-based methodology is being developed to supplement engineering judgment and determine critical locations that are candidates for careful analysis, and monitored during testing and operation. The methodology uses a formal pairwise error metric that determines the relative error in the system reliability should a limit state be filtered. The methodology was demonstrated on T-38 lower wing skin. Continuing studies concern the damage tolerance analysis of 133 holes located in a T-38 longeron.

Project C5, "Identifying Structurally Significant Items Using Matrix Reanalysis Techniques," attempts to resolve the critical issue that future aircraft platforms are likely to have minimal information about their combined thermo-mechanical-acoustic operational environment and no information about their failure rates. As a result it is highly unlikely that traditional factors of safety will provide the same level of reliability. Ravi Penmetsa (WSU) and Eric Tuegel (AFRL/RBSM) lead a team working to provide component designers for these future platforms, the safety factors and maintenance requirements to minimize operational costs. In this research, a Boeing 707 lower wing skin with stiffeners was used as an example to demonstrate the proposed risk assessment process. This process is developed along the lines of the Failure Mode Effects and Criticality Analysis (FMECA) that is used in reliability engineering, along with a Risk Priority Number (RPN) that unifies all the structural components into a single comparison metric irrespective of their failure mode and discipline.

C1 Uncertainty/Risk Quantification Methods for STATS (Song, Lee, Tuegel)

The goal of the project is to develop novel stochastic methods that quantify the uncertainty and risk of spatially tailored aero-thermal structures (STATS) using advanced computational simulations. The primary focus is on methods that identify important input uncertainties, which will enable us to put the priority of limited resources on the dominant uncertainties during condition based maintenance as well as risk-informed design of aircraft structures.

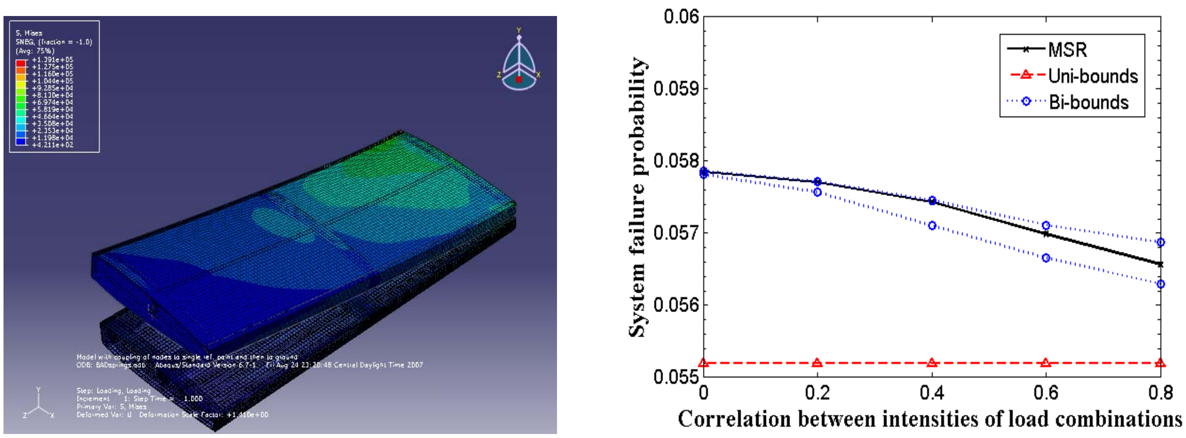

Figure Son-1. ABAQUS wing torque box model and system reliability analysis result.

First, we developed a computing tool to perform reliability analysis of STATS by use of a widely-used finite element (FE) software ABAQUS in conjunction with a Matlab-based, open-source reliability analysis software FERUM. As an example structure of the project, we created an ABAQUS FE model of a generic aircraft wing torque box through collaboration with researchers in AFRL and MSSC. We per-

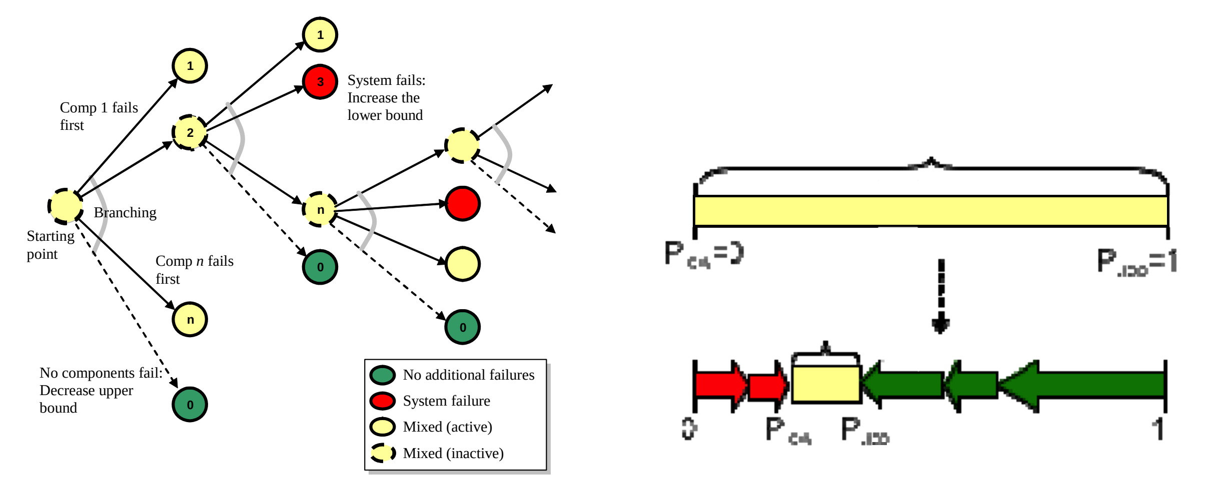

Figure Son-2. Procedure of the B^3 method and sequential updating of the system failure bounds

formed "system" reliability analysis of the wing box, i.e. computed the probabilities of system failure events defined as logical functions of multiple component limit states, using the developed computing tool. The details of the study were presented in the 10th AIAA Nondeterministic Approaches conference (2008). Figure Son-1 shows the developed ABAQUS wing torque box model and the system failure probabilities computed by the system reliability analysis.

One of the major failure modes of aircraft structures is caused by crack nucleation and propagation induced by cyclic loading fatigue. Due to various uncertainties in materials, loadings and mathematical models, and the complex effect of load redistribution during crack propagation, it is a challenging task to identify important uncertainties relative to the fatigue-induced failure of a system. As the first step toward the development of fatigue system reliability analysis method, we performed a literature review on probabilistic fracture mechanics and structural progressive collapse. During this review, we identified merits of existing methods as well as research needs. In particular, we surveyed branch and bound methods, crack growth models, and the uncertainty quantification method such as dimension reduction (DR) method that will be useful for the risk/uncertainty quantification of STATS using computational simulations.

Based on these findings and discussions with AFRL researchers, we developed a recursive formulation of the limit state function of time varying crack length. This new formulation enables us to account for the effect of the stress redistributions caused by multiple crack growth during stochastic fatigue analysis. We also developed a new **b**ranch and **b**ound method using system reliability **b**ounds, termed the 'B^3 method.' Figure Son-2 illustrates the procedure of the method and the updating of the bounds. Recent application of the B^3 method to a three-dimensional truss structure confirmed that the method enables us to estimate the risk of a progressively failing structure accurately with minimum cost of structural analysis. In addition, the method enables us to identify most critical failure paths in the decreasing order without neglecting critical paths. The method was successfully applied to a three-dimensional truss structure and is being applied to more complex structures to present the method through journal publications. Currently, the B^3 method is being further developed for quantifying the uncertainty in the crack length, which is essential for the condition-based maintenance of aircraft structures.

As a test bed example of the developed methods, a tapered beam model has been under development. The initial design and its design requirements were decided through discussions with AFRL researchers. Based on the suggestions, an initial ABAQUS model and its representative loading conditions were developed. Figure Son-3 shows the initial ABAQUS model and FE analysis results. After further development, we will apply the B^3 method to this tapered beam model to demonstrate the method and to identify further research needs.

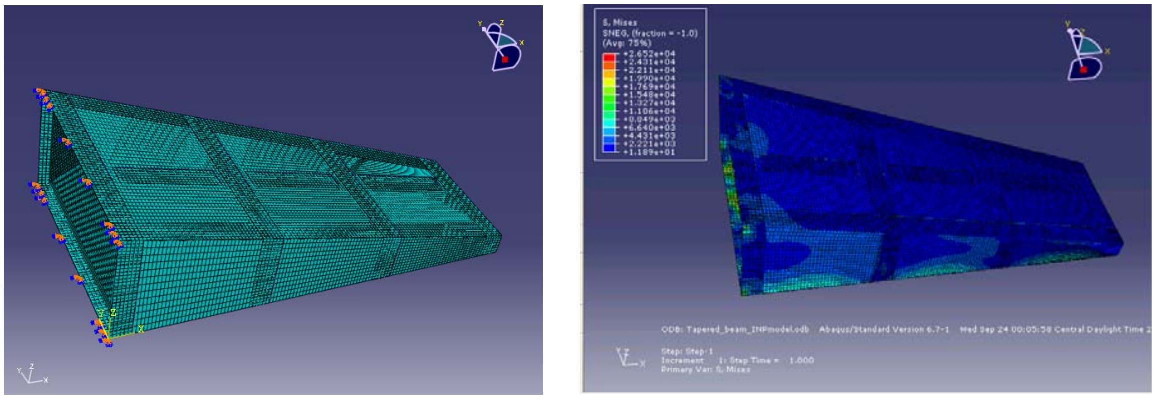

Figure Son-3. Initial tapered beam model and FE analysis result.

C2 Validation of Simulations Having Uncertainties in Both Simulation and Experiments (Brandyberry, Gruenwald, Haney)

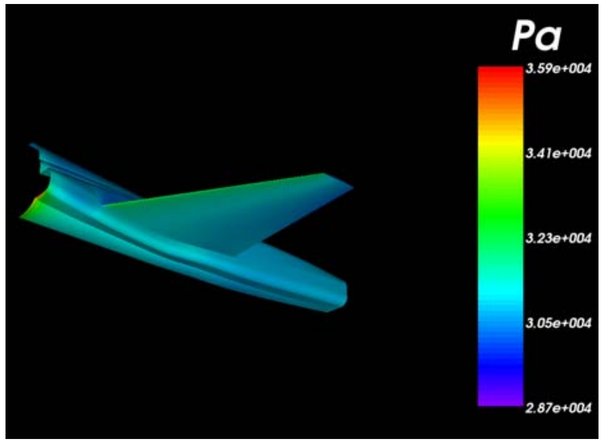

Figure Bra-1. CFD-generated pressure distribution on wing and section of fuselage that will be applied to ABAQUS solid mechanics model of wing.

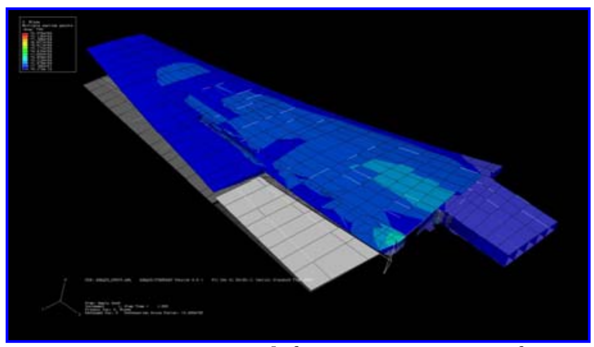

Figure Bra-2. ABAQUS deformation response of applied pressure shown in Figure 1 (displacement accentuated in figure to allow visual observation of displacement). Color illustrates stress in wing.

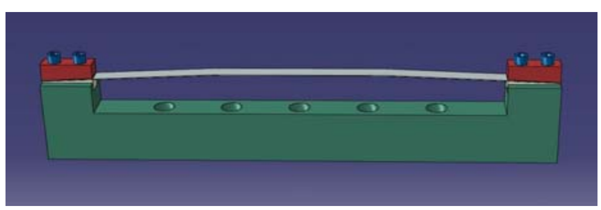

Figure Bra-3. ABAQUS model of clamped-beam experimental setup. Entire assembly will be vibrated normal to the clamped beam, and modal response of beam to different vibrations will be observed.

Over the past year, progress has been made in development and application of the surrogate-clustering uncertainty propagation methodology previously reported. Extension of the method to a coupled fluid-structure interaction (FSI) problem modeling the structural wing response of an Air Force training jet has been assembled, allowing estimation of the uncertainties in the coupled simulation. A combination of computational fluid dynamics (CFD) simulations (using the *Rocstar* simulation suite – Figure Bra-1) of a half-model of the trainer and an ABAQUS solid mechanics model of the wing (Figure

Bra-2) have been combined with uncertainty estimates in both CFD and solid mechanics input parameters to generate uncertainty estimates of wing stresses and displacements for the coupled simulation.

The coupled FSI problem modeling is ongoing, but no experimental data currently exists to compare to the results of the modeling. In order to enable validation modeling using both computational and experimental results with uncertainties, an ongoing experiment involving structural dynamics has been identified which will ultimately generate rich experimental results for comparison to ABAQUS computations. The new problem involves creating a nonlinear reduced order model of a non-planar clamped-clamped beam (Figure Bra-3). Currently, work is ongoing to generate a method to construct an appropriate reduced-order surrogate model for use in the surrogate-clustering uncertainty propagation method. This reduced order model model will then be used in conjunction with a full non-linear ABAQUS model of the experiment as the full-order model. This will allow propagation of uncertainties in the simulation to estimate the uncertainty in the simulation system response quantities (SRQs). Finally, once experimental results are available, techniques for comparing the simulation and experimental results will be developed.

There are no generally accepted methods for comparing dataset with uncertainty, and research is ongoing in how best to perform comparisons and generate appropriate metrics. Leveraging work being performed in the Center for Simulation of Advanced Rockets (CSAR), a computer program to compare two two-dimensional planes of simulation/experimental data has been constructed, with several different difference metrics (mean-squared-error, maximum difference, etc). Computational and experimental results are both currently available from a project funded by the US Navy through a Small Business Technology Transfer Research (STTR) project to IllinoisRocstar LLC and UI, which will be used to explore techniques for comparing simulation/experimental data until Air Force experimental data is available. Once two deterministic planes of data may be compared, extension to comparing uncertain planes of data will be explored. Extension to three dimensions is anticipated. Use in cases where full planes/volumes of uncertain data are not available (i.e., limited experimental data) will then be explored as well.

Finally, work in decision theory is ongoing, leveraging complementary work being performed in CSAR, in an attempt to bring non-mathematical considerations into the validation process. In any program needing to determine whether or not simulation results are “valid” for the application at hand, there are always questions as to what level of agreement is required, which then leads to questions of the use of the simulations and potential impacts of the simulations being invalid (life safety, programmatic impact, financial impact, etc). The use of simulation in design processes is currently being reviewed with the goal of generating generic sets of questions to be answered in a decision approach to validation, which may then be coupled with validation metrics generated from a simulation/experimental program.

C4 System Reliability with Correlated Failure Modes (Millwater, Smith, Sparkman, Wieland, Tuegel)

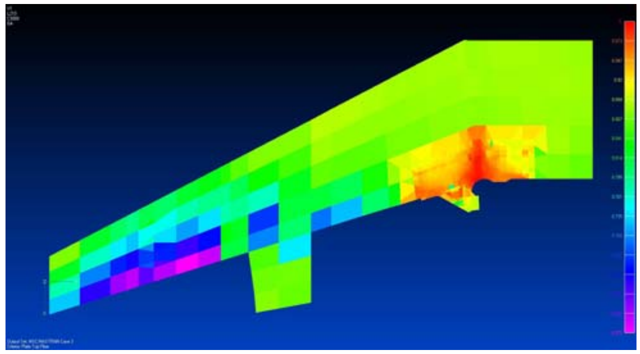

Figure Mil-1. Correlation of stresses to high stress location in root radius

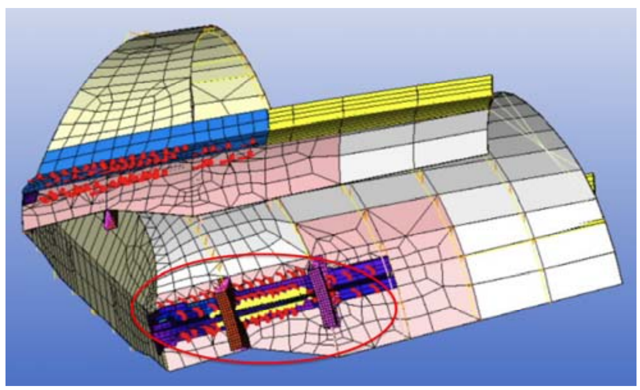

Figure Mil-2. T-38 longeron damage tolerance analysis

New aircraft systems are likely to be constructed of novel materials, operate in extreme environments, and be of limited productions runs. As a result, experience-based methods for determining critical failure locations and failure modes may be lacking. Therefore, a systemic reliability-based methodology was developed to supplement engineering judgment and determine critical locations that are candidates for careful analysis and monitoring during testing and operation.

The methodology uses a formal pairwise error metric that determines the relative error in the system reliability should a limit state be filtered. The error metric considers the relative probabilities of failure and the correlation between limit states. Limit states with a filtering error above a threshold are kept and those below filtered. An efficient numerical method to evaluate the relative error was implemented that obtains accuracy to approximately 10^{-16}. Second order bounds are used to estimate the cumulative effect of all limit states. Both FORM (First Order Reliability Method) and sampling approaches have been developed that use the error metric as a bases for determining critical limit states.

The methodology was demonstrated using a T-38 lower wing skin analysis among others. Foiur different load cases were created and analyzed: (i) ultimate flight condition, which represented the greatest loading expected to be seen by the wing and included both bending and torsion, (ii) subsonic fatigue, (iii) supersonic fatigue, and (iv) landing. Random variables were the stiffnesses of the nine different materials in the model (10% coefficient of variation) and the yield strength of the lower wing skin (3.3% coefficient of variation). The methodology indicated that the root radius was the critical location. Figure Mil-1 shows

the correlation between all other locations and the root radius. Continuing studies concern the damage tolerance analysis of 133 holes located in a T-38 longeron as shown in Figure Mil-2 (longeron region highlighted in red).

C5 Identifying Structurally Significant Items using Matrix Reanalysis Techniques (Penmetsa, Kable, Shanmugam, Tuegel)

Any structural system has a load path, or paths, that transfers applied loads to the attachment points through the structure. The goal of a designer is to use the least amount of material to accomplish this task with high reliability. This reliability can be achieved by either introducing redundancy, which increases weight, or by selecting components that can survive operational loads even in the presence of uncertainties in loading and material properties, and geometric tolerances. Traditionally, reliability has been introduced implicitly through various factors of safety, which have demonstrated low failure rates for metallic aircraft structures. However, for future platforms with minimal information about their combined thermo-mechanical-acoustic operational environment and no information about their failure rates, it is highly unlikely that the traditional safety factors will provide the same level of reliability. Therefore, to design components for these future platforms, the designer needs to ensure that the components satisfy various safety and maintenance requirements with minimal operational costs.

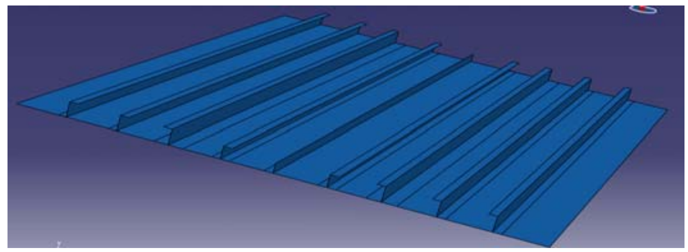

Figure Pen-1: Boeing 707 lower wing skin.

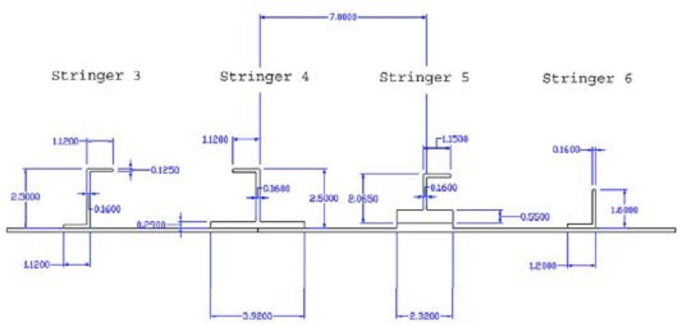

Figure Pen-2: Stiffener geometry (dimensions in inches).

There are certain structural members on an aircraft like the wing attach points, longerons on the fuselage, etc., whose failure results in the immediate loss of the aircraft. Other structural features, such as fastener holes, can have cracks developing that lead to an unscheduled/scheduled maintenance and unavailability, but are not catastrophic failures. Every structural member would fall into one of these categories or a combination of the two. Unfortunately these failures can be located in the internal cavities of the structure and become visible only with a complete teardown. Hence, knowledge of the structural failure modes of all structural components and their consequences is vital for a reliability or risk centered design and maintenance process. Investigation of the above-mentioned scenarios will enable development of a quantitative and qualitative risk assessment and management process.

In this research, a Boeing 707 lower wing skin with stiffeners was used as an example to demonstrate the proposed risk assessment process. This process is developed on the lines of a Failure Mode Effects and Criticality Analysis (FMECA) that is used in reliability engineering. FMECA incorporates Severity (S) of damage, probability of damage Occurrence (O), and damage Detection (D) into a single framework and provides metrics to quantify safety critical and maintenance critical items. Each of these components is assigned values from 1 to 10 based on the structural failure characteristics. For situations where component failure results in a catastrophic damage, S is assigned 10; where the damage can be handled during a routine scheduled maintenance, S is assigned 1. Similarly for highly probable events, O is assigned 10 and for relatively low probability events lower values are assigned to O. Finally a value of 10 is assigned for D to represent a damage location that requires a complete teardown analysis. A value of 1 is assigned for damage that is visible during a routine pre-flight check. The product of these three numbers is called a

Component	Potential Failure Mode	Severity "S"	Occurrence "O"	Detection "D"	RPN= S*O*D
Lower Wing Skin	Fracture of Stringer 2	2.5	3.1	5	38.7
	Fracture of Stringer 3	2.8	3.1	5	43.4
	Fracture of Stringer 4	3.8	1.0	5	19.0
	Fracture of Stringer 5	3.9	1.0	5	19.5
	Fracture of Stringer 6	2.5	7.6	5	95.0
	Fracture of Stringer 7	3.6	1.0	5	18.0
	Fracture of Stringer 8	3.8	1.0	5	19.0
	Fracture of Stringer 9	3.0	3.1	5	46.5
	Fracture of Stringer 10	2.7	3.1	5	41.8

Table Pen-1: Failure Mode Effects and Criticality Analysis (FMECA) for Wing Panel

Risk Priority Number (RPN) that unifies all the structural components into a single comparison metric irrespective of their failure mode and discipline.

These RPN can be determined by exploring all the potential failure modes of the structure and its consequences. This process results in proactive risk management as opposed to a reactive management process that is initiated only after reliability issues are identified. FMECA improves reliability by eliminating or monitoring the single point failure locations. Table Pen-1 shows the final RPN values for the Boeing 707 lower wing panel. Details can be found in [Penmetsa, R.C., Kable, B., and Tuegel, E., 2009. "Identifying Structurally Significant Items using Matrix Reanalysis Techniques," 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Palm Springs, CA, May 4-7, 2009, AIAA 2009-2259]. These values agree with the findings in the literature that were based on both design and in-service cracks observed.

D — Experimentation, Verification, and Validation

Three critical projects enable the completed circle of design–simulation–implementation. An "Experimental Investigation of Thermomechanical Fatigue Failure Modes" (D1) is led by Huseyin Sehitoglu (UI) and Mike Spottswood (AFRL/RBSM). Successfully modeling fatigue in aerospace structures requires detailed knowledge of the various structural and material failure modes across the very wide variety of fatigue loadings possible. In this project we conducted a series of experiments to determine the relative importance of low cycle, high cycle and fatigue crack growth in titanium subjected to thermomechanical fatigue. To understand how such microstructural inhomogeneities affect fatigue damage accumulation in Ti, this work characterized the spatial distribution of residual deformation at the mesoscale (a few grains) and at the macroscale (hundreds of grains) in titanium subjected to cyclic tensile loading. DIC was employed to track and understand the strain fields evolved under the fatigue loading.

John Lambros (UI) and Michael Spottswood (AFRL/RBSM) have teamed with their colleagues in the "Development of Experimental Techniques for Validating a Coupled Thermomechanical Fatigue Simulation Framework" (D2). The objective of this project is to develop experimental techniques for extreme environments such as thermomechanical fatigue. For this reason, Hastelloy X, a nickel-based alloy commonly used in extreme environments, was chosen for experimentation.

"Thermomechanical Fatigue of Hastelloy X: Role of Combined Loading on Material Response," project D3, continues from the earlier work of project D1 that dealt with investigating Ti and Ti alloys. In this effort Digital Image Correlation (DIC) has been applied to measure the coefficient of thermal expansion of Hastelloy X. Using carefully designed induction heating to ensure uniform temperature distribution, samples were heated to temperatures in the range of 30-650 °C. Special sample preparation procedures were developed to enable the use of DIC for displacement measurements at such elevated temperatures.

D1 Experimental Investigation of Thermomechanical Fatigue Failure Modes (Sehitoglu, Efstathiou, Spottswood)

To understand how such microstructural inhomogeneities affect fatigue damage accumulation in Ti, this work characterized the spatial distribution of residual deformation at the mesoscale (a few grains) and at the macroscale (hundreds of grains) in titanium subjected to cyclic tensile loading.Grade 2 pure titanium (α) has a hexagonal close-packed crystal structure. It is known that these low-symmetry crystal structures do not have sufficient slip systems to accommodate an arbitrary deformation, and therefore the collective behavior of grains, and grain-grain interactions become increasingly important. This can lead to significant heterogeneous deformation development at the microstructure. Three loading cycles, shown in Figure Seh-1, produced an increasing amount of incremental plastic strain. Using *ex situ* digital image correlation (DIC), which was described in last year's report, we compared the strain fields obtained at optical magnifications ranging from 3.2x to 50x. Numerous images at higher magnifications have to be assembled to encompass the same field-of-view observed at lower magnifications. Figure Seh-2 shows the residual axial (horizontal direction) strain field induced by the second loading cycle for the same area of the sample, as obtained using three different magnifications. The corresponding grain pattern is shown in the right of Figure Seh-2. The strain fields at the highest optical magnification (50x) reveal deformation patterns that are not detectable at lower magnifications. These deformation patterns appear as inclined slip bands near grain boundaries and grain boundary triple points, with the bands sometimes crossing into neighboring grain interiors.

Continuing this process, it is experimentally or numerically impractical to assemble strain fields from the nanometer to the millimeter length scale. Instead, it is commonly assumed that such defects are averaged, or homogenized, based on a representative volume element (RVE) of material. Here we can probe the length scale of an RVE under plastic deformation con-

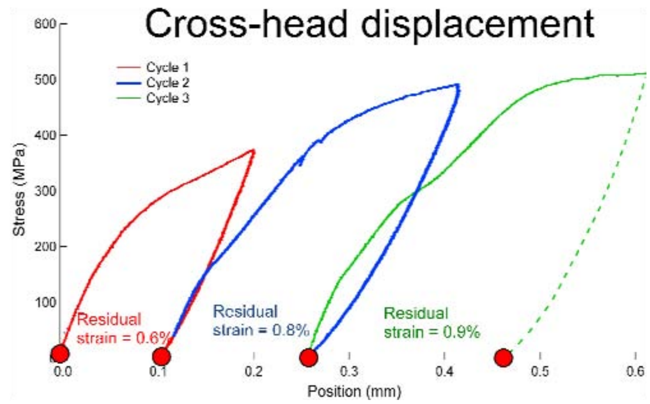

Figure Seh-1: Nominal stress-displacement curve obtained from the cross-head displacement. Red circular markers indicate when images were acquired. Residual strain measurements are listed for each individual load cycle.

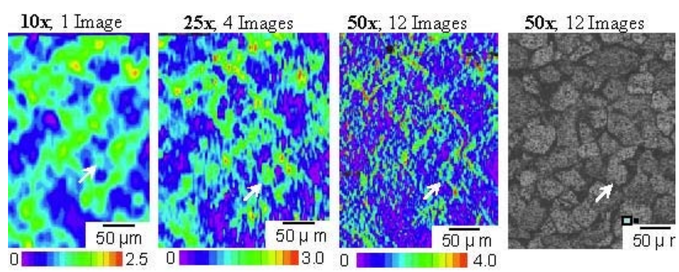

Figure Seh-2: Axial strain field obtained at 10x, 25x, and 50x magnification. Also shown is sample surface with 10x and 50x subset size shown above micron bar. Color bar is in % strain.

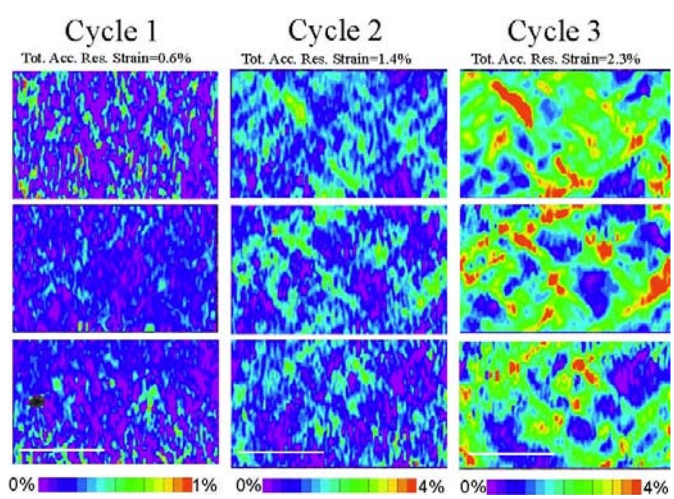

Figure Seh-3: Axial strain fields at three locations along the specimen width obtained after cycle 1 (0.6%), cycle 2 (1.4%), and cycle 3 (2.3%). Strain fields represent total accumulated residual strain after each cycle. Scale bar is 100 μm long.

ditions using the data of Figure Seh-2. The determination of a "plastic RVE" is done by calculating the standard deviation of the average strain at various length scales for the same strain field. The estimated RVE length scale was nearly three times the average grain diameter (i.e., 27-40 grains in 3D) if extracted from the 50x results. The estimate of the RVE length scale was smaller at lower magnifications, which was due to a homogenizing effect caused by the lower measurement resolution. Thus, care must be taken when experimentally obtaining RVE length scale estimates.

The issue of how damage accumulates was probed by performing the *ex situ* residual strain calculation after each of the three successive loading cycles. The results from a 25x magnification are shown in Figure Seh-3. The first column represents the residual strain after the first loading increment, the second column represents the total accumulated residual strain of the first plus the second load increment, and the third column represents the total accumulated from all three load increments combined. Plastic deformation appears somewhat uniform after the first load increment, and becomes nonuniform after the second, with the plastic deformation initially localizing at triple points and then moving towards the interior of grains. At the completion of the third load increment, the strain field has developed regions with significantly larger strains, and consequently at this length scale it appears spatially somewhat more homogeneous again. Note, however, that the deformation pattern after the third load increment has a significant numerical strain heterogeneity which ranges from approximately 0-4% even though the nominal value should be 2.3% (and the average value is very close to that).

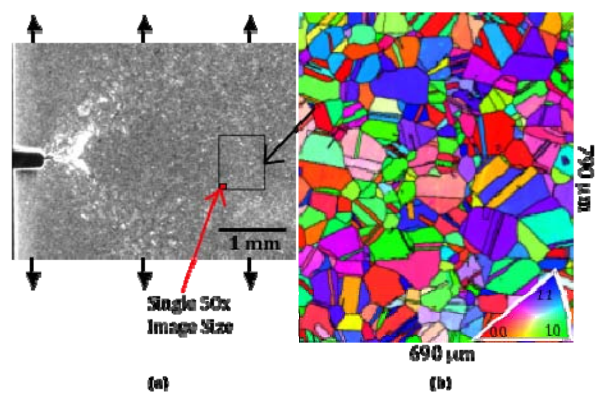

Figure Car-1: (a) Cracked specimen in the load frame with an outline of the region of interest. (b) EBSD was performed on the region to obtain grain geometry and orientation. The region was imaged in an optical microscope (at 50x) by a series of 96 images.

D2 Development of Experimental Techniques for Validating a Coupled Thermomechanical Fatigue Simulation Framework (Carroll, Lambros, Spottswood)

The objective of this project is to develop experimental techniques for extreme environments such as thermomechanical fatigue. For this reason, a nickel-based alloy, Hastelloy X was chosen for experimentation. This material has proven to be a good material for high temperature studies because of high strength and modulus of elasticity at elevated temperatures.

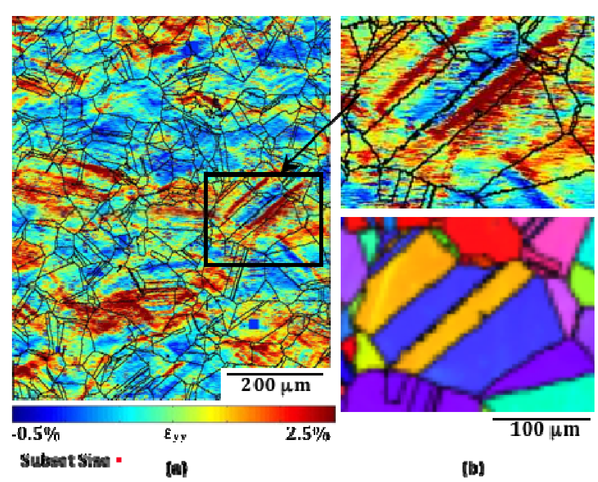

Figure Car-2: (a) DIC strain field perpendicular to the crack covering the entire region of interest. (b) A portion of the strain field has been enlarged to compare it to grain geometry and orientation information obtained through EBSD.

Since fatigue damage initiates and accumulates at the grain level, our experimentation will focus on microscale techniques with sub-grain level resolution. A high magnification level is required in order to make grain level strain surements with digital image correlation (the same technique used in our earlier experimentation). However this requires that multiple images be taken to cover a collection of several grains. An optical microscope at 50x magnification (87 nm/pix) allows for significant sub-grain level resolution in digital image correlation (DIC) measurements; however, the area covered by a single image at this magnification is relatively small (105 µm by 140 µm—about the size of one

grain). To address this issue, multiple overlapping images (up to about 100) were captured in the microscope at 50x and stitched together to obtain a high-resolution image over a much larger region (690 μm by 790 μm), such as the black region shown in Figure Car-1a. Subsequently, DIC measurements were made using the stitched high-resolution images. A large part of this procedure was developed by project D1 in this collaborative activity.

Although using optical microscope images for DIC gives higher resolution strain measurements, this technique is only able to capture *ex situ* images as follows: First, the notched specimen was finely polished and analyzed in a scanning electron microscope (SEM). Grain geometry and microstructure were obtained over the region of interest by performing electron backscatter diffraction (EBSD). Locating the EBSD region's exact position on the sample's surface is important for aligning DIC measurements with microstructural features. The location of the EBSD region in relation to the notch was determined by capturing a series of secondary electron images at a lower magnification covering the entire specimen width. Next, an optical microscope was used at 50x magnification to image the region of interest using 96 images that were subsequently stitched together to form the DIC reference image. The single edge-notched tension specimen was then placed in a servo-hydraulic load frame and loaded in fatigue cycling until a fatigue crack initiated at the notch. Figure Car-1 shows the cracked specimen with an outline of the region of interest (Figure Car-1a) and the corresponding grain orientation map from EBSD (Figure Car-1b).

After the fatigue crack had grown to a total length of 1.5 mm (24,000 cycles), the specimen was removed and images of the deformed specimen were captured using the optical microscope. DIC was performed on the two sets of microscope images to obtain the residual strain fields introduced by the growing fatigue crack. By carefully aligning features in the optical microscope images and the SEM images, the DIC results can be compared to the local microstructure as seen in Figure Car-2. One region of the field is enlarged in Figure Car-2b to highlight a specific feature of the strain field. Two large slip bands have formed within the twinned region of the grain (colored in yellow). In future work, such regions will be examined in relation to the specific orientation of the grains of interest—information that is directly available from the EBSD results.

D3 Thermomechanical Fatigue of Hastelloy X: Role of Combined Loading on Material Response (Abuzaid, Sehitoglu, Spottswood)

Continuing from the earlier work of project D1 that dealt with investigating Ti and Ti alloys, in this effort Digital Image Correlation (DIC) has been applied to measure the coefficient of thermal expansion of the nickel-based super alloy, Hastelloy X. Using carefully designed induction heating to ensure uniform temperature distribution, samples were heated to temperatures in the range of 30-650 °C. Special sample preparation procedures were developed to enable the use of DIC for displacement measurements at such elevated temperatures.

One of the problems encountered was surface change due to oxidation upon heating which drastically changed the sample surface speckle pattern, thus affecting DIC measurements. To address this issue, samples were finely polished to 0.3 microns, heated in an oven to 1000 °C and held at that temperature for five minutes to allow homogenous surface oxidation. After quenching in water, a fine speckle pattern was applied to the surface using a Si powder. This procedure prevented significant pattern changes due to additional oxidation when the sample was then heated in the load frame. However the direct use of DIC for temperatures beyond 650 °C was not possible because surface glowing became significant. To validate the DIC measurements between 30 and 650°C, the thermal expansion coefficient of Hastelloy X was measured over this entire range and found to be in good agreement with literature values (around 15-20 microstrain/C°).

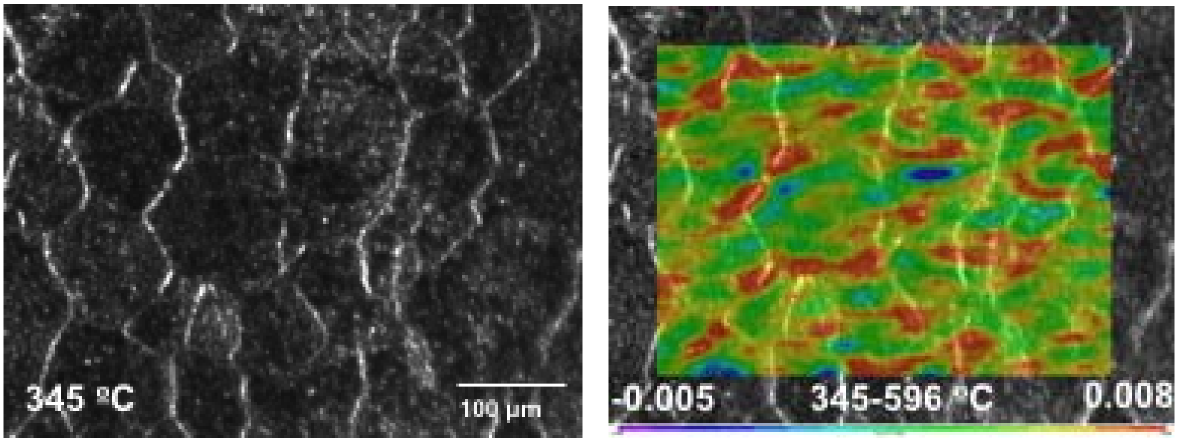

Figure Abu-1: (Left) Reference image of a sample heated to 345 °C; (right) Vertical Strain field for a specimen heated from reference state of 345 °C to a deformed state of 596 °C. Full field results were used to calculate the coefficient of thermal expansion.

An additional feature of the surface preparation process was that it revealed the material grain boundaries by oxidation. This allowed *in situ* high magnification measurements (14x magnification) at the grain level and at high temperature (up to 650°C), as shown in Figure Abu-1a. As was the case in our earlier room temperature deformation experiments on Ti, even for the case of unconstrained thermal expansion, DIC at the grain level reveals sub-grain inhomogeneities in the resulting strain field (Figure Abu-1b). In contrast, the corresponding far field result (around 1.5 x magnification) gives a homogeneous strain field. This is expected to have important implications in thermomechanical fatigue (TMF) damage evolution. In preparation for TMF experiments that can now be done in the range 30-650°C, new control software for TMF has been developed. This program synchronizes mechanical and temperature loading while capturing deformed images throughout the loading cycles. It will be put to use in the near future.

There is interest in extending DIC measurement to temperatures higher than 650°C, even if correlation between temperatures may not be possible. To allow DIC testing at higher atures (650-1000 °C), samples were painted with a high-temperature paint and then speckled with Si powder. Upon heating beyond 650 °C, the digital image intensity increased proportionally with temperature (Figure Abu-2a,b) because of sample glowing (Figure Abu-2c). As the image brightness increases, the image

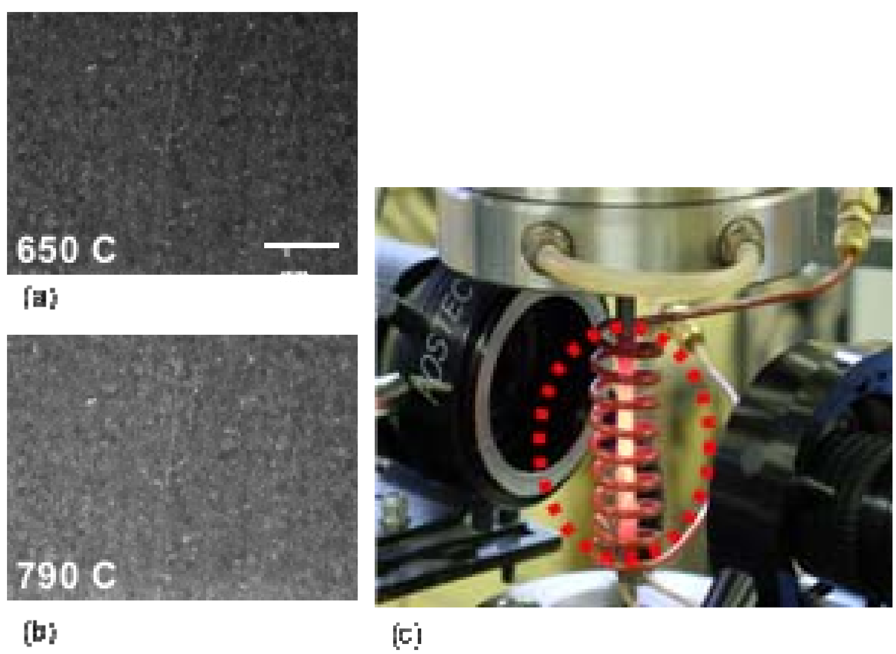

Figure Abu-2: (a) Image at 650 °C; significant surface glowing to be observed upon further temperature increase. (b) Image at 790 °C showing clear lighting changes attributed to surface glowing. (c) Glowing sample heated in the load frame.

sity distribution saturates, thus preventing the use of DIC. However lighting conditions can be adjusted at each specific temperature to guarantee a good image intensity distribution as long as the sample temperature is held constant. This procedure reduces the effect of surface glowing thereby allowing isothermal testing using DIC and was applied for the simple case of tension tests at high temperatures as shown in Figure Abu-3. Each test in the figure is an isothermal elasto-plastic uniaxial loading experiment where the average strains have been measured using DIC.

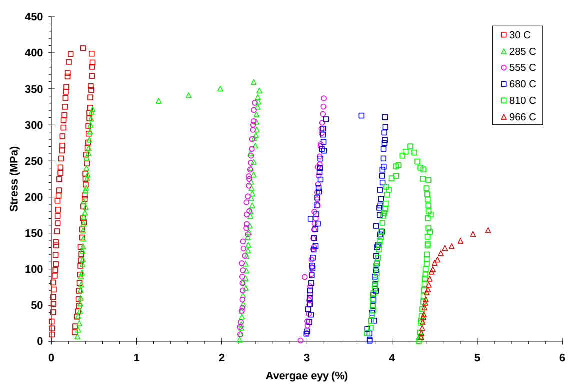

Figure Abu-3: Stress-strain data of Hastelloy X subjected to 6 consecutive loading cycles. Temperature was increased at end of each cycle. For high temp cycles (>650 °C) lighting conditions were adjusted after new temperature set point had been reached. Note strain is an average obtained from full field DIC measurements.

3 Management

Executive Director William Dick manages the Center, and along with two UI co-Technical Directors (Glaucio Paulino and John Lambros) work with their research counterparts at AFRL/RBSM. A Science Steering Committee of program participants (UI and AFRL/RBSM) convenes bi-weekly to guide program execution. Collaboration among the partners is frequent (near-daily) and intense (co-advised research projects and graduate theses, teamed simulation and experiments, co-authored journal articles and project proposal submissions, etc.). Computational resources, graduate assistantships, experimental facilities and visitor office spaces exist at UI to directly support the MSSC. The Directors and Science Steering Committee members are responsible for nurturing the research program, administering the Center, and maintaining and expanding relationships with AFRL/RBSM. This directorate provides the leadership necessary to ensure that the Center identifies the most important research areas, attracts the most qualified researchers, and pursues and completes the work effectively over the long term. A small administrative staff works to execute Center activities.

The MSSC is housed within the University of Illinois Computational Science and Engineering (CSE) Program. CSE is inherently interdisciplinary, drawing faculty, staff and students from 17 departments and requiring expertise in advanced computing technology, as well as in one or more applied disciplines. The purpose of the academic CSE Degree Option is a perfect complement to the goals of the AFRL/RBSM program — to foster interdisciplinary, computationally oriented structural sciences research among all fields of science and engineering, and to prepare students to work effectively in such environments. This academic structure lends itself naturally to the requirements of the MSSC: a free flow of students and ideas across academic departmental, college, and governmental unit lines. A far-reaching Visitors Program has been implemented to encourage close collaboration among the team members. Research offices and computational facilities in CSE space are available for this purpose.

4 Publications

2009

Carroll J., 2009. “Quantifying Grain Behavior with Digital Image Correlation”, Society of Experimental Mechanics Annual Conference, Albuquerque, New Mexico, June 2009.

Carroll J., Efstathiou C., Abuzaid W., Lambros J., Sehitoglu H., Hauber B., Spottswood S.M. and Chona R., 2009. “Observations of Grain Level Damage Accumulation in Fatigue”, SEM International Congress and Exposition, Albuquerque, NM, June.

Carroll J., Efstathiou C., Lambros J., Sehitoglu H., Hauber B., Spotswood S. and Chona R., 2009 “Investigation of Fatigue Crack Closure Using Multiscale Image Correlation Experiments”, Engineering Fracture Mechanics, Vo. 76, No. 15, pp: 2384-2398, DOI: 10.1016/ j.engfracmech.2009.08.002.

Carroll J., Efstathiou C., W. Abuzaid, Lambros J., Sehitoglu H., Hauber B., Spottswood S.M., Chona R., 2009. “Observations of Grain Level Damage Accumulation in Fatigue”, Society of Experimental Mechanics Annual Conference, Albuquerque, New Mexico, June 2009.

Domyancic L., D. Sparkman, and H. Millwater, L. Smith and D. Wieland, 2009. “A Fast First-Order Method for Filtering Limit States,” 11th AIAA AIAA Nondeterministic Approaches Conference, May 4-7, 2009, Palm Springs, CA, AIAA 2009-2260.

Efstathiou C., Sehitoglu H. and Lambros J., 2009. “Multiscale Strain Measurements of Plastically Deforming Polycrystalline Titanium: Role of Deformation Heterogeneities”, in press International Journal of Plasticity.

Gain A. L., 2009. “A hybrid technique to extract cohesive fracture properties of elasto-plastic materials using inverse analysis and digital image correlation,” MS Thesis, University of Illinois at Urbana Champaign.

Gain A. L., Carroll J., Paulino G. H., and Lambros J., 2009. “Extraction of cohesive Properties of elasto-plastic material using inverse analysis,” 10th US National Congress on Computation Mechanics, Columbus, Ohio.

Kang, W.-H., Y.-J., Lee, J. Song, and B. Gencturk, 2009. “Further development of matrix-based system reliability method and applications to structural systems.” Submitted for publication in Structural and Infrastructure Engineering.

Kim D.-J., J.P. Pereira and C.A. Duarte, 2009. “Analysis of three-dimensional fracture mechanics problems: A two-scale approach using coarse generalized finite element meshes.” International Journal for Numerical Methods in Engineering. Accepted for publication.

O’Hara P., C.A. Duarte, and T. Eason, 2009. “Multi-scale analysis of sharp transient thermal gradients using coarse generalized finite element meshes.” In Tenth US National Congress on Computational Mechanics, Columbus, OH, USA, 16-19 July 2009. Keynote Lecture.

O’Hara P., C.A. Duarte, T. Eason, and D.-J. Kim, 2009. “Generalized finite element analysis of three-dimensional heat transfer problems exhibiting sharp thermal gradients.” Computer Methods in Applied Mechanics and Engineering, 198(21—26.:1857—1871, http://dx.doi.org/10.1016/ j.cma.2008.12.024.

Ostoich C., Bodony, D. J., Geubelle, P. H., 2009. “Coupled computational fluid-thermal investigation of hypersonic flow over a quilted dome surface," Bull. Amer. Phys. Soc., Vol 54(19).

Penmetsa R. C., and Tuegel, E., 2009. “Single Inverse Based Reliability Analysis for Static Strength Failure Modes,” International Journal of Engineering under Uncertainty: Hazards, Assessment, and Mitigation, Accepted for Publication, October 2009.

Penmetsa R. C., Kable, B., and Tuegel, E. 2009, "Identifying Structurally Significant Items Using Matrix Reanalysis Techniques," 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Palm Springs, California, May 4-7, 2009.

Penmetsa R. C., Tuegel, E., and Shanmugam, V., 2009. "Rapid Risk Assessment using Probability of Fracture Nomographs," Journal of Fatigue and Fracture of Engineering Materials and Structures, Vol. 32, 2009, pp.-886-898.

Penmetsa, R. C., Shanmugam, V., and Tuegel, E., 2009. "Rapid Risk Assessment using Probability of Fracture Nomographs," Journal of Fatigue and Fracture of Engineering Materials and Structures, Accepted for publication, June 2009.

Shanmugam V., Penmetsa, R.C., and Tuegel, E., 2009. "Determination of Probability Density Functions of the Cohesive Zone Model Parameters" ASTM Committee E08 of Fatigue and Fracture, Atlanta, GA, Nov 2009.

Sucheendran M., Bodony, D. J., Geubelle, P. H., 2009. "Structural-acoustic interaction of a cavity-backed, clamped, elastic plate with sound in a duct," Bull. Amer. Phys. Soc., Vol 54(19).

Watts, Seth, 2009. Issues in Material Microstructure Morphology. Master's Thesis. University of Illinois at Urbana-Champaign.

Watts, S. E., D. A. Tortorelli, T. G. Eason, 2009. Arbitrarily High-Ordered Morphological Descriptors for Quantifying the Microstructure of Metal Matrix Composites. 10th US National Conference on Computational Mechanics. Columbus, OH, 16-19 Jul. 2009.

2008

Carroll J., Efstathiou C., Lambros J., Sehitoglu H., Hauber B., Spottswood S.M. and Chona R., 2008. "Multiscale Analysis of Fatigue Crack Growth Using Digital Image Correlation", SEM International Congress and Exposition, Orlando, FL, June 2008.

Dwire H., Penmetsa, R.C., and Tuegel, E., 2008. Risk-Based Design Plots for Aircraft Damage Tolerant Design, 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Chicago, IL, Apr. 7-10, 2008. AIAA 2008-2077.

Efstathiou C., Carroll J., Sehitoglu H., Lambros J., Hauber B., Spottswood S.M. and Chona R., 2008. "Damage Evolution in Polycrystalline Titanium", SEM International Congress and Exposition, Orlando, FL, June, 2008.

Efstathiou C., Sehitoglu H., Carroll J., Lambros J. and Maier H.J., 2008. "Full-Field Strain Evolution during Intermartensitic Transformations in Single Crystal NiFeGa", Acta Materialia, Vol. 56, pp. 3791-3799.

Hauber B., Brockman R., and Paulino G. H., 2008, On Fatigue Crack Propagation in FGMs: Experiments and Simulations, Multiscale and Functionally Graded Materials Conference (M&FGM 2006), AIP Conference Proceedings, 973, 333-338.

Lee Y.-J., J. Song, and E.J. Tuegel, 2008. Finite element system reliability analysis of a wing torque box. Proc. 10th AIAA Nondeterministic Approaches Conference, April 7~10, Schaumburg, IL.

Nguyen T., Song J., and Paulino G. H., 2008. Probabilistic Fracture Analysis of Functional Graded Materials - II: Implementation and Numerical Results, Multiscale and Functionally Graded Materials Conference (M&FGM 2006), AIP Conference Proceedings, 973, 159-164.

O'Hara P., C.A. Duarte, and T. Eason, 2008. A generalized finite element method for steady-state and transient heat transfer problems exhibiting sharp thermal gradients. In Society of Engineering Science

2008. 45th Annual Technical Meeting, University of Illinois at Urbana-Champaign, Urbana, IL, USA, Oct 2008.

O'Hara, P., C.A. Duarte and T. Eason, 2008. Multi-Scale Finite Element Analysis of Three-Dimensional Heat Transfer Problems Exhibiting Sharp Thermal Gradients. *Computer Methods for Applied Mechanics and Engineering*, Submitted March 2008

Paulino G. H., M.-J. Pindera, R. H. Dodds Jr., F. A. Rochinha, E. Dave and Linfeng Chen, Editors, 2008. <u>Multiscale and Functionally Graded Materials 2006</u>, AIP Conference Proceedings Volume 973; ISBN: 978-0-7354-0492-2.

Smith L., H.R. Millwater, K. Griffin, and D. Wieland, 2008. "Conditional Filtering for Simplification of Aircraft Structural System Reliability Calculation," 10th AIAA Nondeterministic Approaches Conference, April 7-10, Schaumberg, IL.

Smith L., H. Millwater, D. Wieland, K. Griffin, 2008. Advanced Structural System Reliability Methods for Aircraft Structures, presented at the AIAA Structures, Dynamics and Materials Conference, Schaumberg, IL, April 7-10, 2008.

Song J., Nguyen T., and Paulino G. H., 2008, Probabilistic Fracture Analysis of Functional Graded Materials - I: Concept and Formulation, Multiscale and Functionally Graded Materials Conference (M&FGM 2006), AIP Conference Proceedings, 973, 153-158.

Song J., W.-H. Kang, Y.-J., Lee, and S.-Y. Ok, 2008. Applications of matrix-based system reliability method to complex structural systems. Proc. IFIP 08-WG7.5, August 6-9, Toluca, Mexico.

Stump F. V., Silva E. C. N., and Paulino G. H., 2008, Topology Optimization with Stress Constraints: Reduction of Stress Concentration in Functionally Graded Structures, Multiscale and Functionally Graded Materials Conference (M&FGM 2006), AIP Conference Proceedings, 973, 303-308.

Tuegel E., Penmetsa, R. C., and Shanmugam, V., 2008. "Rapid Determination of the Probability of Fracture for a Cracked Stiffened Panel," 2008 ASIP Conference, San Antonio, Texas, Dec. 2-4, 2008.

Watts, S. E., D. A. Tortorelli, T. G. Eason, 2008. Quantitative description of the morphology of a randomly-distributed particulate composite material. 45th Annual Technical Meeting of the Society for Engineering Science. Urbana-Champaign, IL, 12-15 Oct. 2008.

2007

Duarte C.A., P. O'Hara and T. Eason, 2007. Multiscale adaptive modeling of sharp thermal gradients. In Structural Science Center Peer Review, Urbana, IL, Oct. 2007.

Efstathiou C., Sehitoglu, H., Carroll, J., Lambros, J., Maier, H. J., 2007. Full-Field Strain Evolution during Intermartensitic Transformations in Single Crystal NiFeGa, *Acta Mater.*, Submitted.

O'Hara P., 2007. Finite element analysis of three-dimensional heat transfer for problems involving sharp thermal gradients, M.Sc. Thesis, University of Illinois at Urbana-Champaign, Urbana, IL.

O'Hara P., C.A. Duarte and T. Eason, 2007. Adaptive Modeling of Heterogeneous Shells Subjected to Thermomechanical Loads. Poster presentation at Structural Science Center Peer Review, Urbana, IL, Oct. 2007.

O'Hara P., C.A. Duarte and T. Eason, 2007. Analysis of Three-Dimensional Heat Transfer Problems Involving Sharp Thermal Gradients, Ninth US National Congress on Computational Mechanics, San Francisco, CA, Jul. 2007.

Penmetsa R., and Tuegel, E., 2007. Probability Distribution Function of the Product and Ratio of Independent Random Variables using Convolution, *Journal of Multivariate Analysis*, Submitted December 2007

Song J., and W.-H. Kang, 2007. Matrix-based system reliability method and applications to structural systems. Proc. 18th Engineering Mechanics Division Conference of ASCE, ASCE EMD 2007., June 3-6, Blacksburg, VA.

Song J., and W.-H. Kang, 2007. Risk-quantification of complex systems by matrix-based system reliability method. Special Workshop on Risk Acceptance and Communication, Stanford, CA, March 26-27.

Song J., and W.-H. Kang, 2007. System reliability and sensitivity under statistical dependence by matrix-based system reliability method. Accepted for publication in Structural Safety.

Stump F.V., E.C.N. Silva and G.H. Paulino, 2007. Optimization of material distribution in functionally graded structures with stress constraints, Communications in Numerical Methods in Engineering. Vol.23, No.6, pp. 535-551.

2006

Bellur Ramaswamy R., E. Fried, X. Jiao, and D. A. Tortorelli, 2006. Simulating Solid-Solid Phase Transition in Shape-Memory Alloy Microstructure by Face-Offsetting Method, presented at Multiscale and Functionally Graded Materials Conference, Oct. 15-18, 2006, Hawaii.

Dick William A., 2006. Midwest Structural Sciences Center — A University-Government Partnership, Multiscale and Functionally Graded Materials Conference – FGM 2006, Ko Olina, Hawaii, October 2006.

Duarte C. A., L. G. Reno, A. Simone, and E. van der Giessen, 2006. Hp generalized finite elements for three-dimensional branched cracks and polycrystals, In G. H. Paulino, M.-J. Pindera, R. H. Dodds, and F. A. Rochinha, editors, Multiscale and Functionally Graded Materials Conference – FGM 2006, Ko Olina, Hawaii, 15-18 October 2006. Keynote Lecture.

Hauber B.; Brockman, R. and Paulino, G. H., 2006. On Fatigue Crack Propagation in FGMs: Experiments and Simulations, presented at Multiscale and Functionally Graded Materials Conference M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.

Nguyen T.; Song, J. and Paulino, G. H., 2006. Probabilistic Fracture Analysis of Functional Graded Materials - II: Implementation and Numerical Results, presented at “Multiscale and Functionally Graded Materials Conference” M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.

Song J.; Nguyen, T. and Paulino, G. H., 2006. Probabilistic Fracture Analysis of Functional Graded Materials - I: Concept and Formulation, presented at “Multiscale and Functionally Graded Materials Conference” M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.

Stump F. V., Silva, E. C. N. and Paulino, G.H., 2006. Topology Optimization with Stress Constraints: Reduction of Stress Concentration in Functionally Graded Structures, presented at “Multiscale and Functionally Graded Materials Conference” M&FGM 2006, Honolulu, Hawaii, USA, October 15th – 18th, 2006.